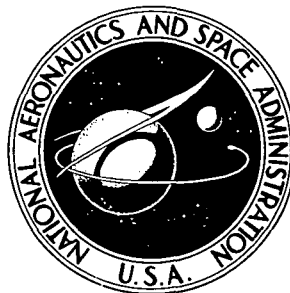NASA TECHNICAL
MEMORANDUM

NASA TM X-2997

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EMISSIONS OF NITROGEN OXIDES FROM
AN EXPERIMENTAL HYDROGEN-FUELED
GAS TURBINE COMBUSTOR

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16. Abstract

The effect of operating variables of a hydrogen fueled combustor on exhaust concentrations of total oxides of nitrogen was determined at inlet-air temperature levels up to 810 K, pressure of 4.14×10^5 N/m^2, and reference velocity of 21.3 m/sec. The combustor, which was originally designed for hydrocarbon fuel produced a NO$_x$ concentration of 380 ppm with hydrogen at 810 K inlet-air temperature. A reduction in NO$_x$ of about 30 percent was obtained by modification to a lean or rich primary zone. The lowest NO$_x$ levels obtained with hydrogen were equivalent to those of the reference combustor burning hydrocarbon fuels.

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SUMMARY

The effect of combustor-inlet conditions when burning gaseous hydrogen on concentrations of total oxides of nitrogen was determined. Test conditions were selected to simulate a supersonic cruise condition for an advanced aircraft turbine engine. The inlet-air temperature level was varied up to 810 K (1460° R) at a pressure level of 4.14×10^5 newtons per square meter (60 psia) and combustor reference velocity of 21.3 meters per second (70 ft/sec). The combustor was operated with four different primary zone equivalence ratios of 0.43, 0.62, 2.84, and 6.00. These ratios correspond to premixed flame temperatures of 1845, 2183, 2012, and 1413 K, respectively. An existing experimental combustor segment designed for hydrocarbon fuel was used in burning hydrogen and produced a reference NO_x emission level of 380 ppm at an inlet-air temperature of 810 K (1460° R) for a primary zone equivalence ratio of 0.62. Reduction in the reference NO_x level was obtained by varying the primary zone equivalence ratio to burn at a lower theoretical flame temperature. The average reduction of NO_x was 22 percent for a primary zone equivalence ratio of 0.43 and 33 percent for a ratio of 6.00.

The lowest NO_x levels obtained with hydrogen were comparable with those of the reference combustor burning hydrocarbon fuels based on volumetric concentration of NO_x for an equivalent enthalpy rise in combustion gases.

INTRODUCTION

Exhaust concentrations of total oxides of nitrogen (NO_x) were determined experimentally in a combustor segment by burning gaseous hydrogen fuel over a range of test conditions simulating those encountered in advanced aircraft turbine engines. These results were compared with NO_x emission data obtained in a previous investigation of ASTM A jet fuel and vaporized propane (ref. 1).

Because of steadily increasing demands for fuels and the urgency to reduce pollution of the atmosphere, hydrogen was investigated as a candidate fuel for advanced turbojet engines (ref. 2). Although hydrogen fuel is relatively expensive, it may become considerably more competitive with fossil fuels as their price increases because of increasing demand and decreasing supply.

During the combustion of hydrogen with air to form water a small amount of NO_x is produced as a byproduct. The formation of NO_x can be related exponentially to the flame temperature and linearly to the dwell time (additional factors such as combustor pressure affect NO_x formation to a lesser degree). Thus, from the standpoint of NO_x formation takeoff and supersonic cruise conditions are of importance since the combustor operates at high temperature levels and maximum production of NO_x occurs at these conditions. Since one of the ways of reducing NO_x is control of the primary-zone equivalence ratio, the use of hydrogen is attractive because of its wide range of flammability limits which provide flexibility of control of the flame temperature.

In order to experimentally determine the effect of primary zone equivalence ratio (i. e., flame temperature levels) on NO_x formation, the experimental vapor combustor of reference 1 was selected. This combustor was used previously for hydrocarbon fuels and does not represent a configuration that would take advantage of the unique combustion properties of hydrogen. However, the primary-zone equivalence ratio could be easily varied to obtain different flame temperature levels, and the method of fuel introduction approaches a simple premixed system as discussed in reference 1. Tests were conducted for inlet-air temperatures up to 810 K (1460° R) at 4.14×10^5 newtons per square meter (60 psia) pressure over a range of overall equivalence ratios of 0.115 to 0.22, by operating at primary-zone equivalence ratios of 0.43, 0.62, 2.84, and 6.00. Emission concentrations of NO_x were obtained and compared with those of gaseous and liquid hydrocarbon fuels on the basis of an equivalent increase in enthalpy of combustion gases.

APPARATUS AND PROCEDURE

Test Facility and Instrumentation

The test combustor was mounted in the closed-duct facility described previously in reference 1 and shown in figure 1. Tests were conducted at a pressure level of 4.14×10^5 newtons per square meter (60 psia). Combustion air drawn from the laboratory high-pressure supply system was indirectly heated up to 810 K (1460° R) in a counterflow U-tube heat exchanger. The temperature of the air flowing out of the heat exchanger was automatically controlled by mixing the heated air with varying amounts of cold bypassed air. Airflow through the heat exchanger and bypass flow system and the total pressure of the combustor inlet air-flow were regulated by remotely controlled valves.

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Combustor instrumentation stations are also shown in figure 1. The inlet-air temperature was measured at station A with eight Chromel/Alumel thermocouples. Inlet-total pressures were measured at the same station by four stationary rakes consisting of three total-pressure tubes each. The total-pressure tubes were connected to differential pressure strain gage transducers that were balanced by wall static pressure taps located at the top and bottom of the duct. Combustor outlet temperatures and pressures were obtained with a traversing exhaust probe at station C. The probe consisted of 12 elements: five aspirating platinum/platinum - 13-percent-rhodium total-temperature thermocouples, five total-pressure probes, and two wedge-shaped static-pressure probes. At station D a four-point air-cooled probe sampled the exhaust. Station D was located 0.914 meter (36 in.) downstream of the combustor exhaust in a circular pipe with a diameter of 0.508 meter (20 in.).

Experimental Combustor

The combustor used in this investigation was similar to combustor model number 1 of reference 1 in which vapor fuel was injected through a series of eight evenly spaced 0.94-millimeter (0.037-in.) diameter holes (60° included angle) located on a 1.75-centimeter (0.69-in.) diameter. A schematic of the combustor is shown in figure 2. The main portion of the airflow entering the snout was admitted into the combustor by means of air swirlers. A small portion, approximately 6 percent of the total flow, was used to film cool the sides of the combustor. The dilution air was admitted by means of external scoops.

The mass flow distribution was varied in this series of tests. The reference combustor operated with a primary zone equivalence ratio of 0.62 (referred to an overall equivalence ratio of 0.215). Higher primary equivalence ratios of 2.84 and 6.00 were obtained by blocking off the snout inlet. An equivalence ratio of 0.43 was obtained by using the maximum snout open area (40 percent of the duct cross-sectional area), adding five holes 2.22 centimeters (0.875 in.) in diameter in the upper wall similar to the five holes in the lower wall, and assuming 50-percent recirculation.

Gas Sample Technique

The exhaust gas sample was withdrawn through the four-point air-cooled stationary probe shown in figure 3. The gas sample probe was located downstream of the traversing probe and in the center of the exhaust stream at station D as shown in figure 1. The gas sample, at approximately 2.07×10^5 newtons per square meter (30 psia) pressure, was passed through an electrically heated sampling line at a temperature of approxi-

mately 423 K (760° R) to the gas analyzer. To prevent contamination in the sample line, a nitrogen purge was used before and during combustor ignition.

The exhaust gas was analyzed for the oxides of nitrogen by means of a chemiluminescent meter. The meter included a converter for reducing NO_2 to NO. Measurement of NO with and without the converter allows determination of both NO and NO_2; however, in this study only the total oxides of nitrogen are reported. Approximately 10 percent of the total oxides of nitrogen were present as NO_2 in the sample for the range of test conditions investigated in this study.

Combustor Test Conditions

The combustor was operated at a constant total inlet pressure of 4.14×10^5 newtons per square meter (60 psia) and reference velocity of 21.3 meters per second (70 ft/sec). The inlet-air temperature level was varied in three steps: 590 K (1060° R), 700 K (1260° R), and 810 K (1460° R). Data were obtained for each of the four combustor geometry variations in which the primary zone equivalence ratio was varied from 0.43 to 6.00.

RESULTS AND DISCUSSION

The NO_x emission levels presented in this report are expressed on a volumetric basis as discussed in the appendix. In this study the combustion efficiency data as calculated from thermocouple measurements indicated a level of the order of 100 percent (±1.5) for all test conditions.

Effect of Overall Equivalence Ratio

The effect of overall equivalence ratio on NO_x emission is presented for three inlet-air temperatures in figure 4 for the reference combustor configuration, which operates with a primary zone equivalence ratio of 0.62. As the overall equivalence ratio increases the NO_x emission level increases. The NO_x level for an overall equivalence ratio of 0.22 is 380 ppm at an inlet-air temperature level of 810 K (1460° R). The increase in NO_x with variation in overall equivalence ratio is in part due to the fact that the primary zone equivalence ratio is actually not constant. The air distribution was fixed and the fuel flow varied; consequently, at low fuel flows burning would occur in a leaner mixture. As the fuel flow increases to the referred overall equivalence ratio of 0.22 the quoted primary zone equivalence ratio is attained (0.62).

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The reference combustor used for these tests was the unmodified combustor of reference 1 which used a combination vapor and liquid fuel nozzle injector. Gaseous hydrogen was injected through eight orifices located on a diameter within the air swirler as indicated in figure 2. This same configuration had also been used to burn vapor propane and, by adding a simple nozzle at the center of the assembly, liquid ASTM A jet fuel. In figure 5 comparisons of the NO_x emission levels obtained with these alternate fuels and the hydrogen fuel data from figure 4 are presented at an inlet-air temperature of 700 K (1260° R). Liquid fuel data were taken at 10.34×10^5 newtons per square meter (150 psia). For comparison with the hydrogen and vaporized propane data at 4.14×10^5 newtons per square meter (60 psia), NO_x values for ASTM A jet fuel were reduced by the square root of the inlet pressure ratio. Comparison of the NO_x emission, assuming a constant heat release corresponding to a temperature rise of approximately 650 K (1200° R) (i.e., equivalence ratio of 0.26 for the hydrocarbons and 0.215 for hydrogen), indicated that about 99 percent more NO_x (245 ppm) was formed with hydrogen than with vaporized propane (124 ppm), and about 54 percent more NO_x formed than with liquid jet fuel (158 ppm). Note that the same ratio in overall equivalence ratio for constant enthalpy rise between hydrogen and hydrocarbons is reflected in the primary zone equivalence ratio; that is, for the fixed reference geometry the hydrogen design equivalence ratio is 0.62 when burning hydrocarbons is 0.75.

Effect of Primary Zone Equivalence Ratio

In figure 6 the effect of overall equivalence ratio on NO_x emission using hydrogen is shown for four primary-zone equivalence ratios at three levels of inlet-air temperature. For all inlet temperatures operation at a primary-zone equivalence ratio of 0.62 (that of the reference combustor) produced the highest NO_x emissions. At inlet-air temperatures of 590 and 700 K, the NO_x emissions were reduced approximately 20 and 30 percent, respectively, by operation at either leaner (0.43) or richer (2.84 and 6.00) primary-zone equivalence ratios. At an inlet-air temperature of 810 K, NO_x emissions exhibited a greater dependency on equivalence ratio than at the other inlet-air temperatures. At equivalence ratios of 0.43 and 6.00, NO_x emissions were reduced approximately 22 and 33 percent, respectively, from the values obtained at an equivalence ratio of 0.62.

Effect of Inlet-Air Temperature

The effect of inlet-air temperature on NO_x concentrations is shown in figure 7 for four primary-zone equivalence ratios and a constant overall equivalence ratio of 0.215.

The curves were obtained from a crossplot of figure 6 to illustrate the increase in NO_x emission with increasing inlet-air temperature. At the lean primary zone equivalence ratio of 0.43 the NO_x emission level increased from 93 to 260 ppm as the inlet-air temperature was increased from 590 to 810 K (1060° to 1460° R).

In figure 8 NO_x emissions obtained with the lean primary zone equivalence ratio are compared with NO_x emissions using vapor propane and ASTM A jet fuel for a constant temperature rise of 650 K (1170° R). Comparison of the NO_x emissions indicated that the emission level was about 42 percent greater with hydrogen than with vaporized propane (185 ppm) for an inlet-air temperature level of 810 K (1460° R). Comparison of the NO_x emissions obtained with hydrogen and ASTM A jet fuel indicate that similar levels of NO_x were produced up to inlet-air temperature levels of 700 K (1260° R). Data for comparison at higher inlet-air temperatures were not obtained with ASTM A jet fuel.

Comparison of Experimental Data and Theoretical NO_x Concentration

In figure 9 the theoretical nitric oxide (NO) emission level for hydrogen combustion is presented over a range of equivalence ratios at an inlet-air temperature level of 800 K (1460° R) and 4.14×10^5 newtons per square meter (60 psia). Two theoretical curves are presented: (1) an equilibrium curve and (2) a curve that represents a primary-zone dwell time of 2.5 milliseconds.

Theoretical chemical kinetics calculations were performed to determine formation rates for nitric oxide by using the computer program of reference 3. A premixed-prevaporized reaction was assumed. These computations were initiated by using the equilibrium compositions calculated from reference 4 for hydrogen. Since combustion reactions were assumed to occur instantaneously, the calculated equilibrium compositions were used as the initial reactant concentrations with the exception that the initial nitrogen oxide concentrations were set to zero. The nitric oxide producing reactions occurred at a constant reaction temperature equal to the equilibrium flame temperature for each given value of equivalence ratio. Since nitric oxide is the predominant oxide of nitrogen formed during combustion, the theoretical results will be limited to this particular species. Seven intermediary kinetic reactions are considered in this computation, but the principal reactions forming nitric oxide are the so-called Zeldovitch reactions between (1) nonatomic oxygen and diatomic nitrogen and (2) monatomic nitrogen and diatomic oxygen. The equilibrium curve indicates that a high level of NO would be formed even at lean equivalence ratios of the order of 0.1 to 0.2. In a typical turbojet combustor however, the average primary-zone dwell time is of the order of 2 to 3 milliseconds, so that equilibrium would not be achieved. The results of the chemical kinetics computation are shown for a reaction dwell time of 2.5 milliseconds, which is representative of turbojet combustor primary zones. As shown, appreciable NO formation

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would occur primarily over an equivalence ratio range between 0.6 to 1.8 for a typical turbojet combustor.

Comparing the experimental results with theoretical prediction for a 2.5-millisecond dwell time (fig. 9) indicates that appreciably more NO_x was formed than would be expected assuming a premixed system. The model was based on the assumption that all species, except the oxides of nitrogen, have reached equilibrium. Similar comparisons using hydrogen and hydrocarbons have shown that the nitric oxide concentration predicted is about an order of magnitude lower than either the experimental value or that predicted by a well-stirred reactor model that does not assume equilibrium hydrogen chemistry (refs. 5 and 6). Within the reaction zone the concentration of oxygen atoms can overshoot the equilibrium value by several orders of magnitude at low temperatures (ref. 7). Because the oxygen atom is an important part of the nitric-oxide-producing scheme, a model that assumes equilibrium values cannot predict nitric oxide concentration accurately. Preliminary unpublished data indicate that the model based on equilibrium hydrocarbon chemistry appears to be adequate only for predicting nitric oxide concentrations for fuel-air mixtures near stoichiometric. This result may be due to the high reaction rates near stoichiometric which would minimize any effect of oxygen atom overshoot.

Primary zone equivalence ratio can be related to the calculated flame temperature. The relation between the primary-zone equivalence ratio and flame temperature is shown in the appendix. For primary zone equivalence ratios of 0.43, 0.62, 2.84, and 6.00, assuming the available fuel and air to be uniformly mixed, the calculated flame temperatures would be 1845, 2183, 2012, and 1413 K, respectively. In figure 10 the NO_x emission from figure 6(c) at an inlet-air temperature of 810 K (1460° R) and an overall equivalence ratio of 0.215 is shown for the flame temperature associated with each primary equivalence ratio. As expected the NO_x level decreased as the flame temperature decreased.

As shown in figure 9 the NO_x level should have been significantly reduced at the lean or rich primary-zone equivalence ratios. But, at best, only a 33-percent reduction in NO_x was experienced. There are several plausible explanations as to why a significant reduction in NO_x emission was not achieved. As previously was discussed it is possible that the analytical prediction may be an order of magnitude too low due to oxygen overshoot. Another factor has to do with the mixing process within the combustor itself. The primary-zone equivalence ratio was varied by either blocking off the snout open area or adding holes in the liner wall to increase the primary air recirculation. Blocking off the air at the snout results in less air at the nozzle swirler. Since the swirler area was fixed, the intensity of the vortex was reduced. Thus, the intensity of the mixing between the fuel and air would also be reduced. Coupled with the inherent wide flammability limits and high flame speed of hydrogen it is possible that localized burning at higher flame temperatures than anticipated occurred before the fuel and air had adequately

mixed. Actually, the redistribution of air and fuel within the combustor is even more complex since air that bypasses the snout must now enter through the liner wall. Because the liner wall geometry was not changed a larger pressure drop would result and a more intense recirculation pattern established. A larger combustor liner open area, as for the lean equivalence ratio case, would also change the distribution. The combination of mixing within the fuel and air vortex and the altered recirculation patterns would undoubtedly influence localized burning.

It can be expected that improved mixing between fuel and air would reduce the NO_x emission. A combustor concept that offers improved mixing capability is the swirl-can combustor, which was originally developed for hydrogen fuel (ref. 8). In this concept the mixing is improved and the dwell time reduced by taking advantage of the unique combustion properties of hydrogen. In the swirl-can fuel is injected tangentially into the combustor element and mixed with primary air entering the upstream orifice. Nearly all the airflow except for that required to cool the liner passes either through or directly around the swirl-can. The high flame speed of hydrogen permits rapid burning which is immediately followed by quenching. At the present time there are no experimental data for NO_x emission with the swirl-can configuration and hydrogen fuel, but the swirl-can concept has been applied to burning hydrocarbon fuels. These studies have demonstrated that the NO_x emissions of swirl-can combustors is substantially lower than those of conventional combustors (see ref. 9). Lower NO_x emissions than reported herein may be possible by improved reaction zone mixing such as that used in the swirl-can concept.

SUMMARY OF RESULTS

By substituting hydrogen fuel in an experimental combustor designed for vapor hydrocarbon fuels and burning at test conditions that included inlet-air temperatures up to 810 K (1460° R), a pressure level of 4.14×10^5 newtons per square meter (60 psia), a reference velocity of 21.3 meters per second (70 ft/sec), and overall equivalence ratios to 0.22, the following trends in emission concentrations of total oxides of nitrogen (NO_x) were obtained.

1. The NO_x level in the reference configuration (primary zone equivalence ratio of 0.62) increased as the overall equivalence ratio increased and at an overall equivalence ratio of 0.22 the NO_x level was 380 ppm.

2. Reduction in the reference NO_x level (primary zone equivalence ratio of 0.62) was achieved by varying the primary zone equivalence ratio in order to burn at a lower theoretical flame temperature level. The average reduction in NO_x was 22 percent for a primary zone equivalence ratio of 0.43 (flame temperature 1845 K) and 33 percent for a ratio of 6.00 (flame temperature, 1413 K).

3. Comparison of the NO_x emission levels obtained with hydrogen and hydrocarbon fuels indicated that similar NO_x levels were achieved on a volumetric basis based on an equivalent enthalpy rise of combustion gases.

Lewis Research Center,
  National Aeronautics and Space Administration,
    Cleveland, Ohio, November 20, 1973,
      501-24.

APPENDIX - CONSIDERATIONS IN THE COMPARISON OF NO_x EMISSION

LEVEL OF HYDROGEN WITH HYDROCARBONS

Comparison of selected properties of hydrogen, gaseous propane, and ASTM A jet fuel are shown in table I, as obtained from references 10 and 11.

As shown the flammability limits for hydrogen offer considerable more latitude in the selection of an operating primary-zone equivalence ratio than hydrocarbon fuels. The equivalence ratio is defined as follows:

$$\text{Equivalence ratio} = \frac{\text{Fuel-air ratio}}{\text{Stoichiometric fuel-air ratio}} \qquad (1)$$

Two equivalence ratios are used in this report: one, a primary equivalence ratio in which the average calculated fuel-air ratio in the primary zone is used; and two, an overall equivalence ratio in which the metered values of fuel and air into the combustor are used to determine the fuel-air ratio. Values of the stoichiometric fuel-air ratio are listed in table I.

The primary zone equivalence ratio is related to the theoretical flame temperature as shown in figure 11 for hydrogen and for a liquid jet fuel from reference 3 for an inlet-air temperature level of 800 K (1440° R) and pressure of 4.14×10^5 newtons per square meter (60 psia). This test condition is representative of combustor operation during high altitude cruise at high flight Mach numbers. As indicated in figure 11 the flame temperature level of hydrogen is higher than that for a hydrocarbon fuel; thus, it would be expected that for a given equivalence ratio a higher level of NO_x emissions would be experienced with hydrogen. However, the flame temperature and thus NO_x emissions can be reduced by operating at a lower equivalence ratio.

The NO_x emission levels are expressed in terms of the volumetric concentration in this report. The emission index, grams of NO_2 per kilogram of fuel, may be calculated from the volumetric exhaust concentrations of nitrogen oxides by the following expression:

$$EI = 10^{-3} \left(\frac{M_x}{M_e} \right) \left(\frac{1+f}{f} \right) (x) \qquad (2)$$

where EI is the NO_x emission index in grams of NO_2 per kilogram of fuel burned, M_x is the molecular weight of NO_2, M_e is the average molecular weight of exhaust gases, f is the fuel-air ratio, x is the total concentration of NO plus NO_2 in ppm. Due to the use of the fuel-air ratio term in the equation, the NO_x emission index for hydrogen would be calculated to be nearly three times as high as that of a distillate fuel. However, the

flow rate of hydrogen would be only one-third that of a distillate fuel in order to obtain the same combustor temperature rise. This is due to the higher heating value of hydrogen. Thus, volumetric concentrations (ppm) offer a more realistic basis for comparing emission of hydrogen with that of distillate jet fuels.

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TABLE I. - SELECTED PROPERTIES OF THREE FUELS

Properties	Hydrogen	Propane	ASTM A jet fuel
Boiling point, K (^{O}R)	20 (37)	231 (416)	532 (956)
Lower heating value, J/kg (Btu/lb)	120 (51 623)	46 (19 927)	43 (18 600)
Hydrogen-carbon ratio	----------	0.22	0.16
Spontaneous ignition temperature, K (^{O}R)	840 (1 520)	778 (1 400)	523 (940)
Flammability limits:			
Lean equivalence ratio	0.2	0.53	0.52
Rich equivalence ratio	7.0	2.98	4.03
Flame speed (relative to propane at 1.01×10^5 newtons per square meter	6.8	1.00	0.88
Stoichiometric fuel-air ratio	0.029	0.063	0.067
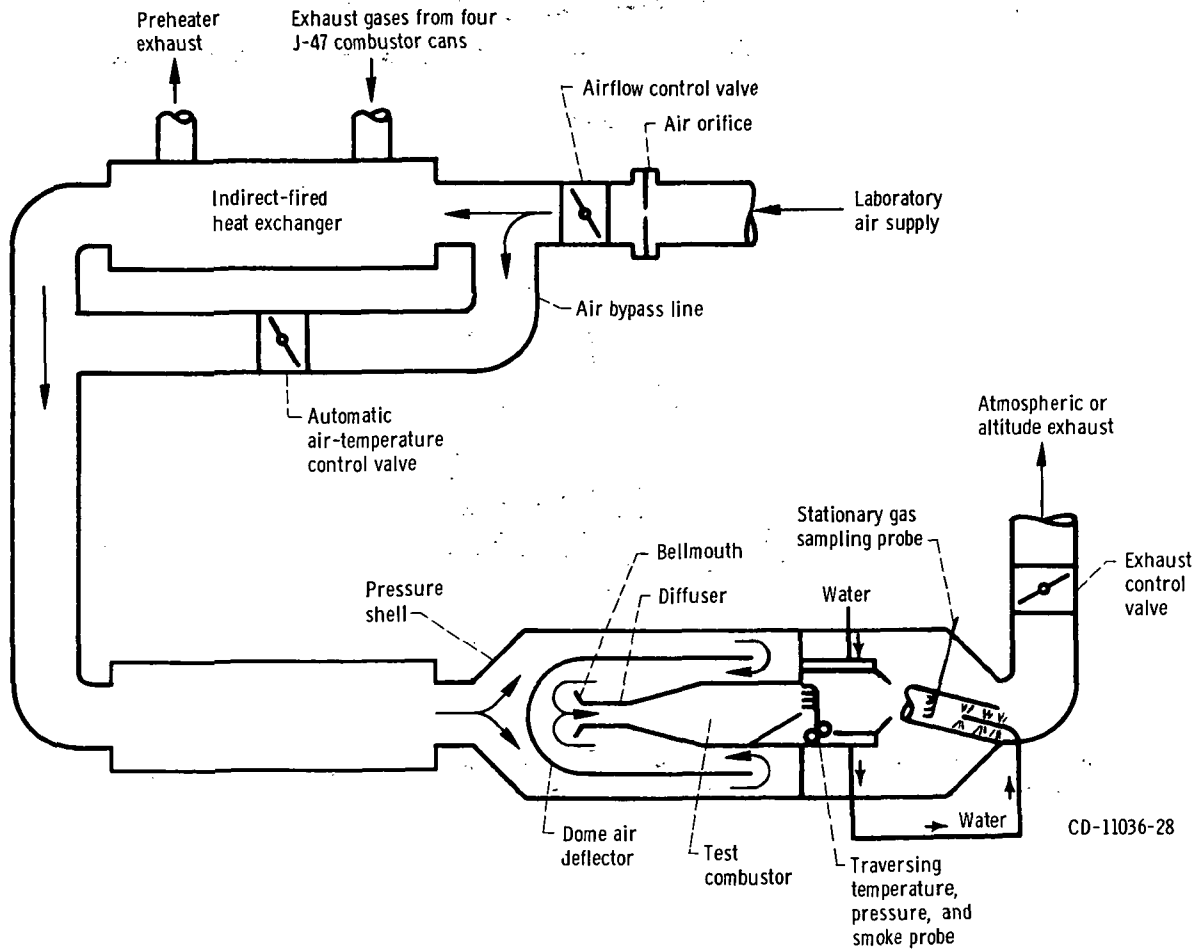
Figure 1. - Test facility and auxiliary equipment.

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(a) Combustor liner.
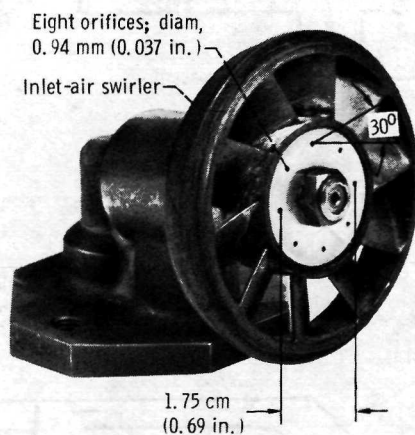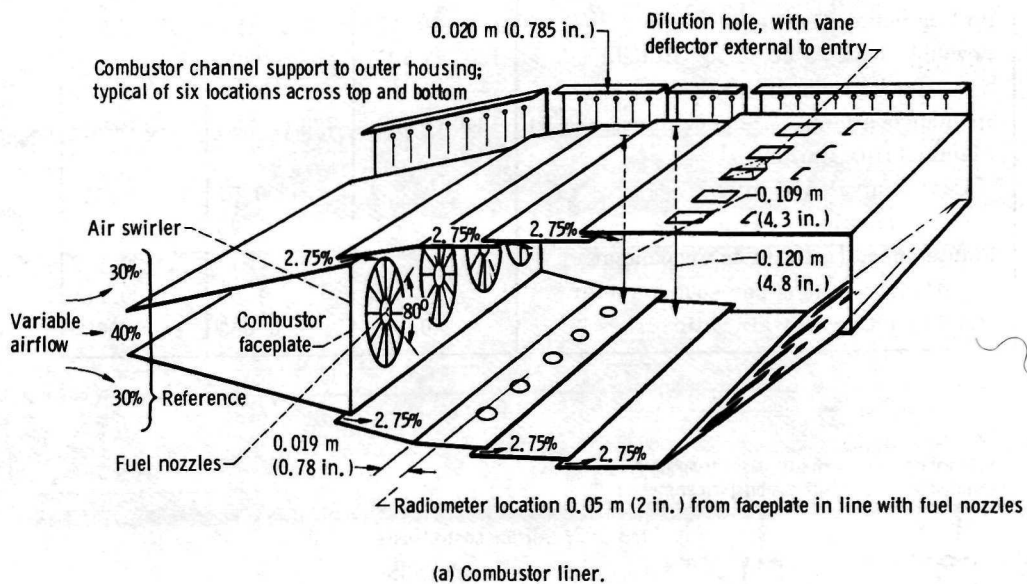
(b) Fuel injector.

Figure 2. - Schematic of combustor liner and fuel injector. Combustor width, 0.31 meter (12 in.); combustor length, 0.32 meter (12.5 in.); maximum combustor housing height, 0.15 meter (6 in.).
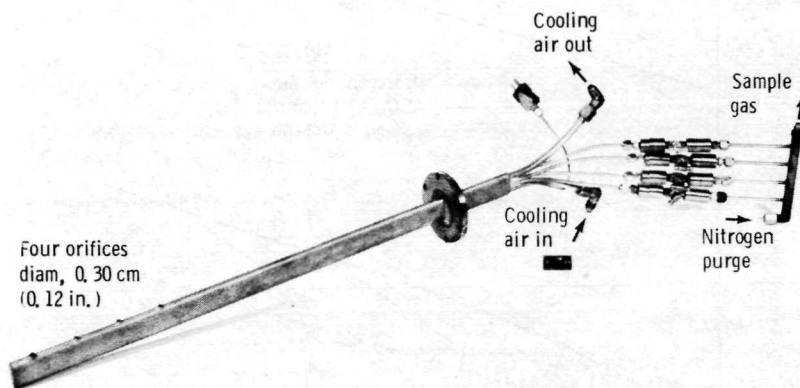
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Figure 3. - Stationary gas sampling probe.
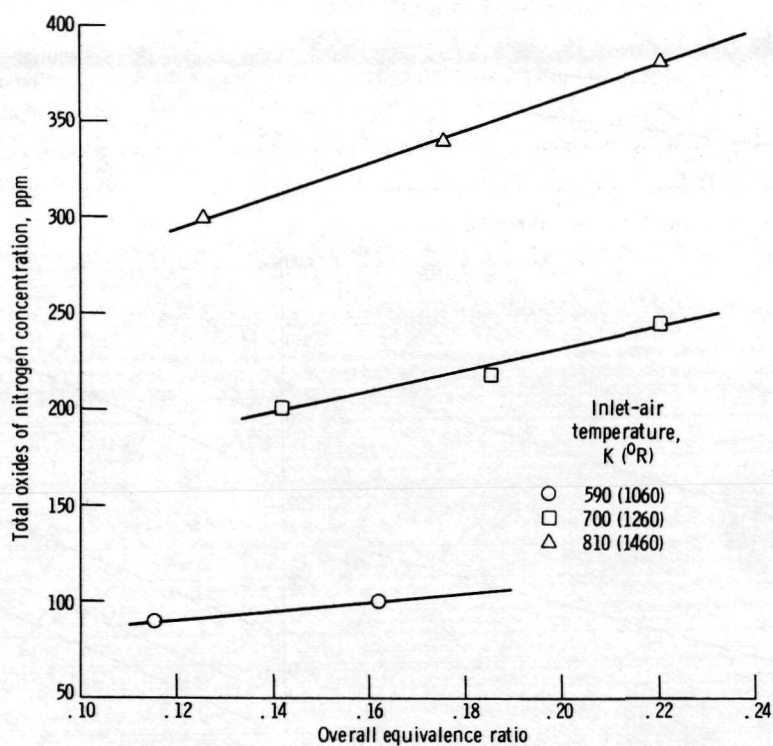
Figure 4. - Effect of overall equivalence ratio on total oxides of nitrogen emission for three values of combustor inlet-air temperature. Inlet-air pressure, 4.14x10⁵ newtons per square meter (60 psia); reference velocity, 21.3 meters per second (70 ft/sec); primary zone equivalence ratio, 0.62.
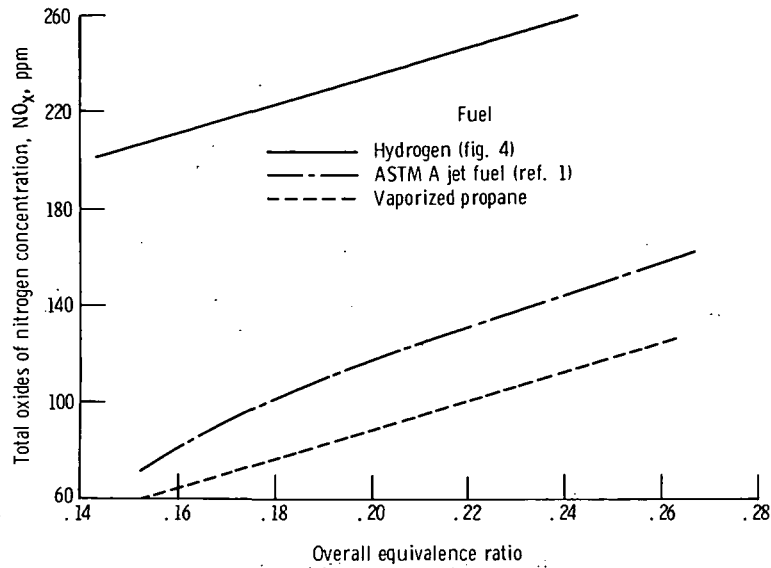
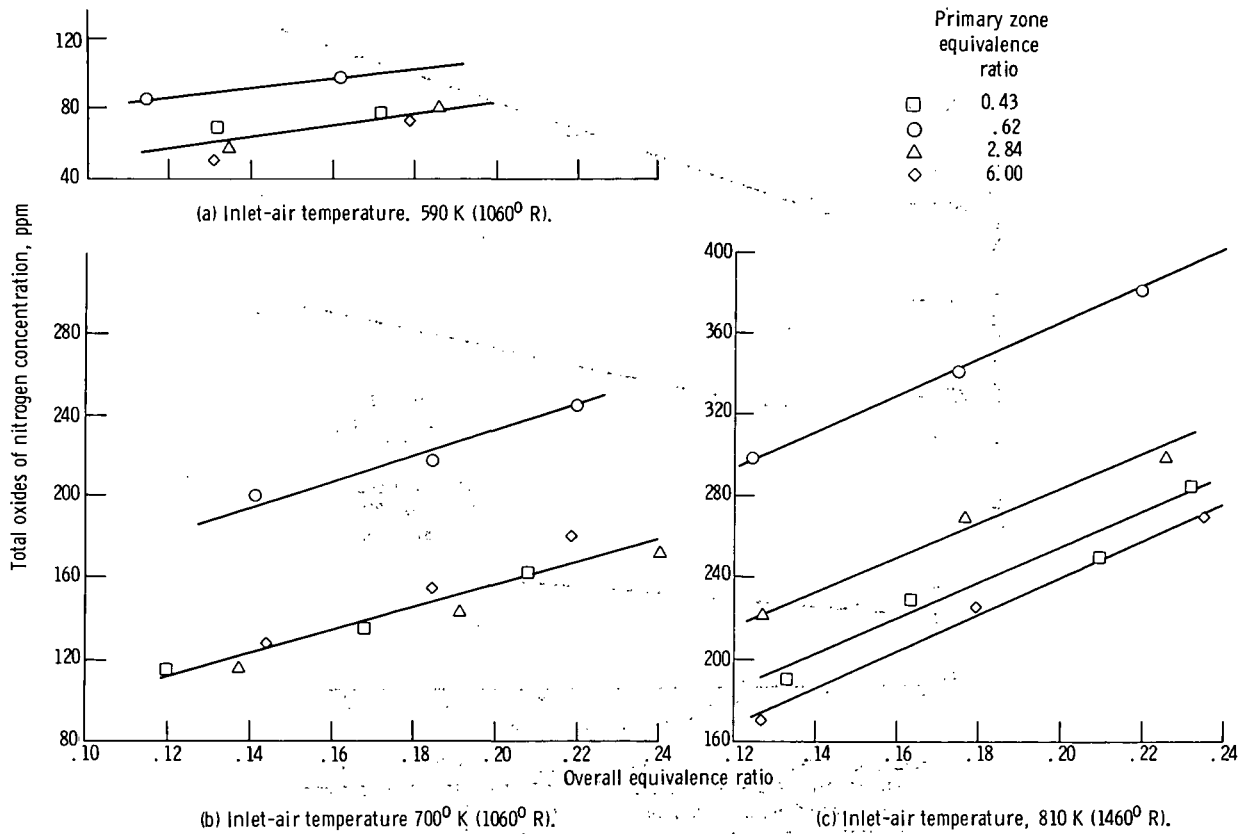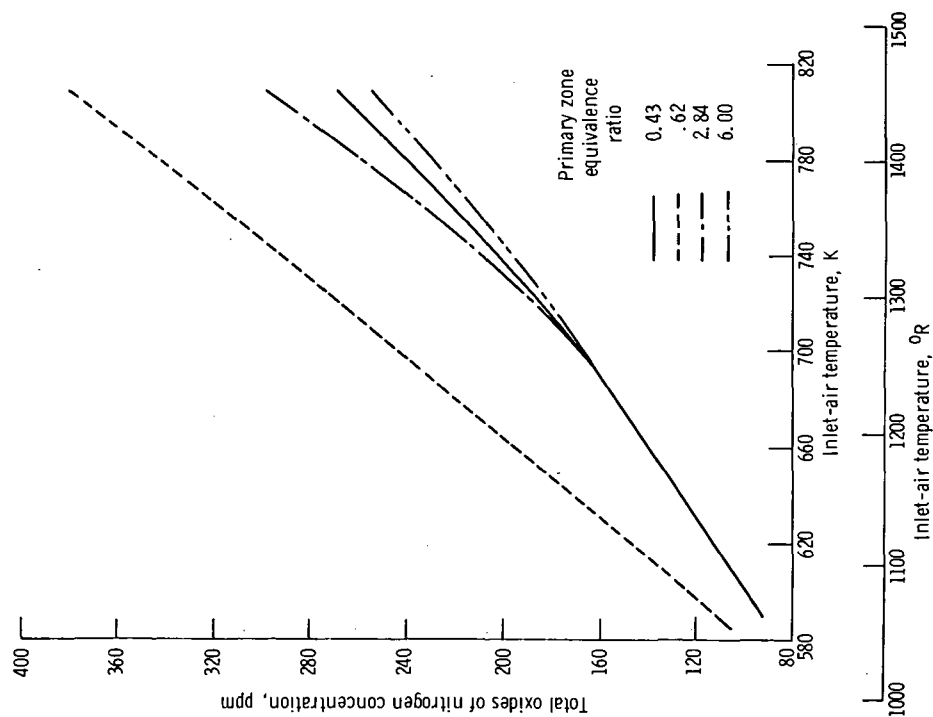Figure 5. - Comparison of oxides of nitrogen emissions. Inlet-air temperature, 700 K (1260° R); pressure, 4.14x10⁵ newtons per square meter (60 psia); reference velocity, 21.3 meters per second (70 ft/sec); hydrogen primary zone equivalence ratio, 0.62; temperature rise, 650 K.

Figure 6. - Comparison of overall equivalence ratio on total oxides of nitrogen emission for four primary-zone equivalence ratios and three inlet-air temperatures. Inlet-air pressure, 4.14x10⁵ newtons per square meter (60 psia); reference velocity, 21.3 meters per second (70 ft/sec).
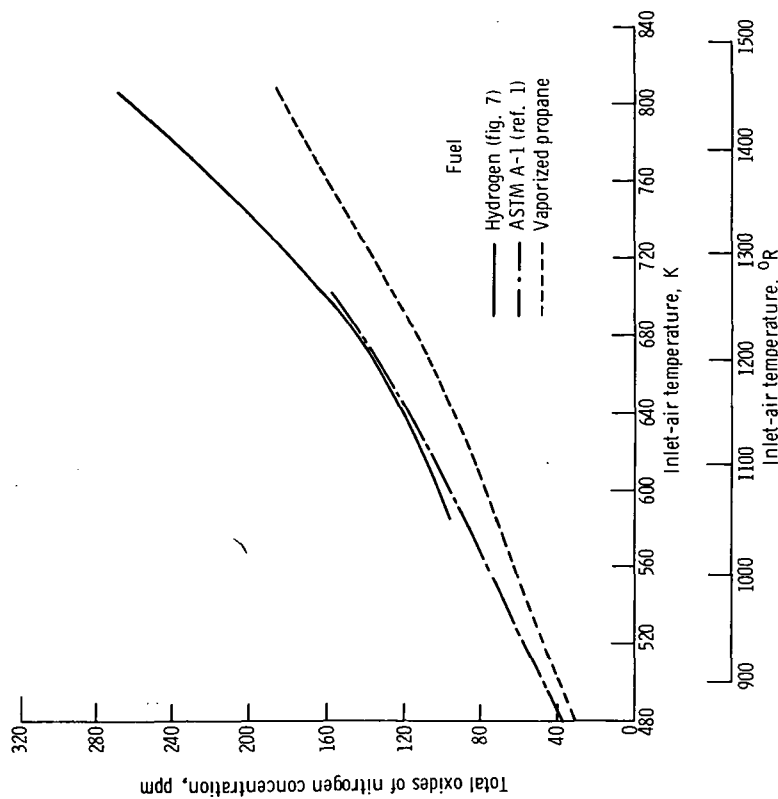
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Figure 8. – Comparison of effect of inlet-air temperature on oxides of nitrogen emission for modified combustor with hydrogen and for reference combustor with liquid ASTM A jet fuel and vaporized propane. Inlet-air pressure, 4. 14x10⁵ newtons per square meter (60 psia); reference velocity, 21. 3 meters per second (70 ft/sec); hydrogen primary zone equivalence ratio, 0. 43; temperature rise, 650 K (1170⁰ R).

Figure 7. – Summary of effect on combustor inlet-air temperature on total oxides of nitrogen for four primary-zone equivalence ratios. Inlet-air pressure, 4. 14x10⁵ newtons per square meter (60 psia); reference velocity, 21. 3 meters per second (70 ft/sec); temperature rise, 650 K (1170⁰ R); overall equivalence ratio, 0. 215.
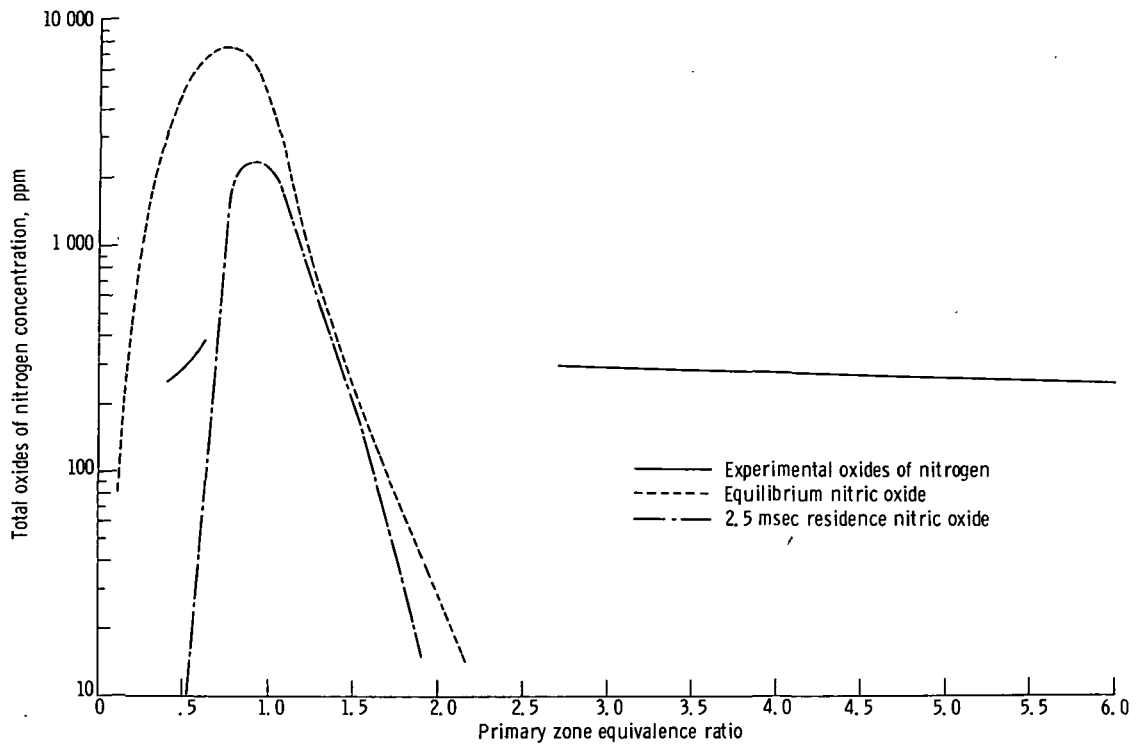
Figure 9. - Comparison of theoretical oxides of nitrogen (as nitric oxide) with experimental results obtained over range of primary zone equivalence ratios. Inlet-air temperature, 800 K; pressure, 4.14x10⁵ newtons per square meter (60 psia); reference velocity, 21.3 meters per second (70 ft/sec); temperature rise, 650 K (1170° R); equivalence ratio, 0.215.
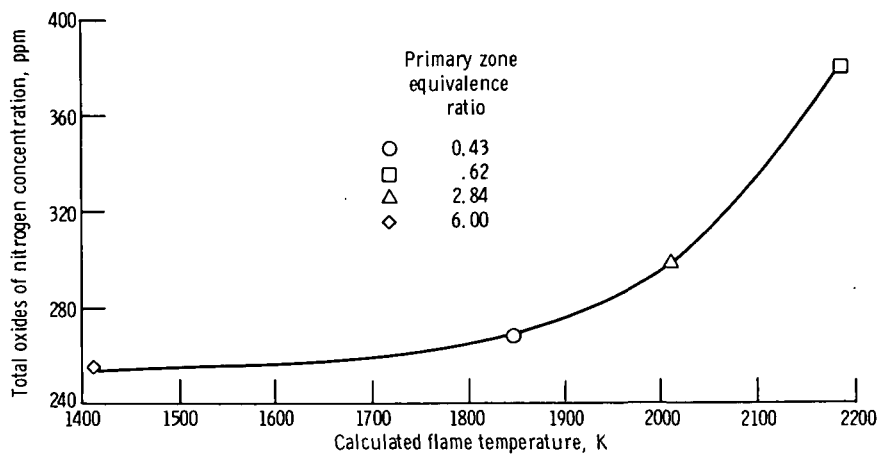

Figure 10. - Effect of flame temperature on the oxides of nitrogen emission. Inlet-air temperature, 800 K; pressure, 4.14x10⁵ newtons per square meter (60 psia); reference velocity, 21.3 meters per second (70 ft/sec); temperature rise, 650 K (1170° R); equivalence ratio, 0.215.
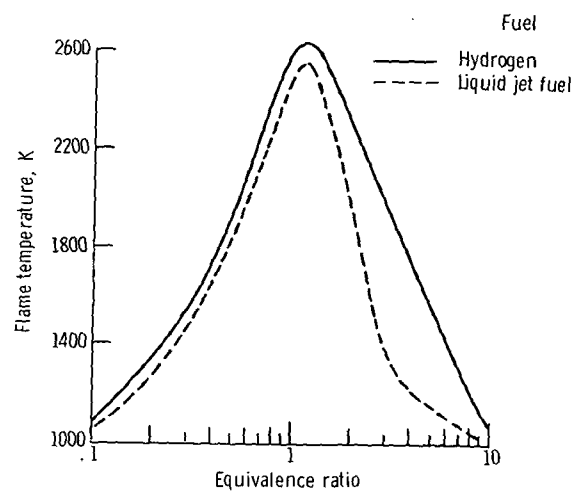
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Figure 11. - Theoretical flame temperature. Inlet temperature, 800 K; pressure 4.14x10^5 newtons per square meter (60 psia).

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